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# Leg preference affects mental representation of single-leg hopping in healthy female adolescents

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**Abstract**
Single-leg hopping (SLH) is a fundamental motor skill in daily activities that is stored as a mental representation. A mental representation is an internal depiction of an action based on prior experience and task comprehension. It is organized through Basic Action Concepts (BACs) and underpins motor planning, execution, and control. This research examines the role of leg preference (either right or left) in the mental representation of SLH among healthy female adolescents. In study 1, we describe the development and validation of the BAC method by using SLH through comparisons between mental representations of children (N = 9; 8–15 years) and young adults (N = 4; 18–24 years). In study 2, we examine the role of leg preference on mental representation through a cross-sectional analysis of 38 healthy female participants (*M* age = 16.07 ± 0.33 years; range = 15.6–16.6). Mental representations of SLH were analyzed by using structural dimensional analysis of motor mental representation (SDA-M). The results of study 1 confirmed the developmental process of BACs by showing that young adults maintain a more structured (i.e., functionally organized) mental representation than children ($p < 0.05$). The results of study 2 revealed more structured mental representations for the preferred leg than for the non-preferred-leg and for the right leg than for the left-preferred leg ($ps < 0.05$). These preliminary findings support age-related cognitive-motor development and may suggest that left hemisphere motor superiority comprises cognitive spheres, namely, enhanced mental representation. Future research into the associations between side preference, cognitive characteristics and motor planning, execution and control is warranted.

**Keywords** Mental representation · Leg preference · Leg dominance · Hopping · Adolescents · Cognition · Action-perception coupling

## Introduction

### Extremity preference in motor skills

Fundamental motor skills, such as hopping, kicking, and throwing, often exhibit a behavioral preference for either the right or left extremity. This preference correspondence with contralateral hemispheric superiority is

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known as laterality[1]. Lateral dominance emerges when one side of the brain governs motor planning, execution, and control[2,3]. The role of laterality in motor performance among children and adolescents has been a topic of interest[1] because of its role in motor control[4]. Sports-related studies[5,6] have recognized the relevance of laterality in sports behavior[7], mechanisms of injury[8] and the development of training protocols[9,10].

While laterality can be advantageous because each side of the brain develops specific competencies[3], ambilaterality (i.e., mixed laterality) is considered advantageous in some sports (e.g., soccer, basketball, and football)[11]. On the other hand, left handedness and ambidexterity are associated with developmental disorders[3,11], such as autism spectrum disorder[12], thereby potentially implying atypical cerebral lateralization[3]. Determining leg preference (also referred to as leg dominance) is more challenging than determining handedness given that the lower limb plays different roles (e.g., supporting vs. gesturing) in motor functions[13]. However, some motor skills, such as single-leg hopping (SLH), involve the same leg for both stabilization and movement, including power generation[14].

## Laterality and motor performance

The association between leg preference and handedness has not been fully established: while 90% of the population is right handed[3], only 77–88% exhibit right leg preference[11]. Furthermore, regardless of their preferred leg, individuals were right-footed for actions involving movement and left-footed for actions involving postural stabilization[13]. These findings suggest task- or goal-dependent laterality[3,15,16].

Conflicting findings regarding differences in motor performance between preferred and non-preferred legs are evident[14,17]. A systematic review of lower extremity performance in physically active healthy participants (N = 264; age range: 16–31 years) revealed non-significant trends in favoring the preferred leg in isokinetic quadriceps and hamstrings strength, the hamstrings-to-quadriceps ratio, vertical jump height, peak vertical ground reaction force during vertical jumping, and SLH distance, including horizontal SLH[14]. The authors suggested that lower limb preference may be related to movement and skill-specific contexts rather than being grounded purely in strength and power measurements. Other studies also reported a lack of inter-leg difference[17], in addition to greater hopping distance and a smaller extended hip angle for the preferred leg in a horizontal hop task. Additionally, significantly greater ($p < 0.01$) single-leg jump distance and vertical and horizontal ground reaction forces (GRFs) were detected for the preferred leg during single-leg and double-leg hop functional tests in healthy college students (N = 24; *M* age = 21.5 ± 1.9 years)[18]. Nevertheless, for the double-leg jump, only the horizontal GRF was significantly ($p < 0.05$) greater for the preferred leg. In contrast, non-significant difference in inter-leg body weight distribution between the preferred and non-preferred legs during the *elevé* (i.e., double-leg heel rise) dance movement was revealed among 23 female dance students (*M* age: 13.57 ± 0.5 years)[6].

## Leg preference and cognition

The role of cognitive-motor mechanisms in leg preference in motor performance most likely encompasses action-perception coupling[19]. Some evidence suggests side-to-side asymmetry in this coupling[20]. One cognitive component potentially underpinning skilled performance is internal motor representation of action (herein referred to as mental representation)[21–23]. This mental depiction of the movement stored in long-term memory includes task-specific spatiotemporal and somatosensory information about the body, the task with its intended effects[24], and the environment[25]. Such information is core to motor planning, execution, and control[26] through the processes of monitoring intentions and motor plans and verifying whether actions match their intended goals[24,25,27].

## Mental representation of action in motor imagery

A mental representation is an internal depiction of an action based on prior experience and task comprehension[24]. It is organized through basic action concepts (BACs)[28,29] and underpins motor planning, execution, and control[24].

Mental representations are used during both physically executed and imaged motor tasks[30,31]. The cognitive process of mentally simulating a motor task without overt physical execution is known as motor imagery (MI)[32,33]. Such mental rehearsal activates similar neural pathways in the brain as those engaged during actual execution of the movement[34,35]. Thus, MI utilizes mental representation of the imaged action[24,36–38]. Neuroimaging studies have suggested that MI involves brain lateralization in the form of a general left hemisphere pattern, which includes mostly the left inferior temporal lobe[39–42]. Accordingly, it is plausible that cognitive processes that address mental representation, including anticipating body configuration movements and specifying their order, involve MI[24,37,43,44].

## Development of mental representation of action

To our knowledge, no prior studies have addressed the role of age in the development of mental representation within the context of SDA-M. However, the ability to effectively use MI for representing movement exists in 5–6-year-old children and progressively develops with further refinement occurring from early adolescence into early adulthood[45]. One study reported comparable MI accuracy in children aged 8–10 and 10–13 years, with the younger cohort significantly differing from adolescents (14–19 years) and young adults (20–29 years)[46]. Modifications in MI ability may differ with age because of, among other factors, maturation of the parietal and frontal cortices, which are involved in sensory-motor integration required for motor planning and execution[45,47].

## Structural dimensional analysis research findings and mental representation side preference

One measurement method that involves such cognitive processes is structural dimensional analysis of mental representation (SDA-M; see Methods section), an established method that measures mental representation[26]. Using the SDA-M showed that expert and non-expert athletes differed from each other in mental representation structure. Specifically, compared with novices, experts showed more structured (i.e., more reliable) patterns of mental representations of motor skills[48,49], regardless of age (e.g., childhood or adolescence). However, young children (ages 6–12) exhibit less structured mental representations than their older counterparts do[49]. Studies employing the SDA-M revealed significant correlations between mental representations and motor execution[50,51] thereby strengthening the test's convergent validity. To our knowledge, no studies have investigated differences in mental representation between preferred and non-preferred extremities using SDA-M.

The association between mental representation and side preference is not fully understood. Limited research suggests an advantage for right hand (i.e., left hemisphere) dominance in tasks associated with mental representation, such as mental rotation of body parts, a cognitive task in which participants make left–right judgments while they are watching pictures of body parts[42,52]. These findings were further supported by a meta-analysis indicating that on a hand laterality mental rotation task, right handers performed better than left handers in general and particularly in identifying right hand pictures. Further support for left-hemisphere superiority in both motor and cognitive functions comes from studies of stroke survivors with left-hemisphere lesions. A study assessing real and imaged hand movements in stroke survivors revealed that participants with left-hemisphere stroke exhibited reduced velocity in both (i.e., contra- and ipsi-lateral) hands, whereas people with right-hemisphere stroke exhibited reduced velocity in the left (i.e., contra-lateral) hand only. Interestingly, these findings were evident for both real and imaged movements, thus supporting left-brain dominance over movement-related cognitive functions (e.g., motor planning and MI)[42]. Studies investigating the association between mental representation and leg preference remain scarce. Understanding this association within the context of functional motor skills that rely on unilaterality, such as hopping, will improve the understanding of action-perception coupling.

### Hopping and the current study

Hopping is a fundamental motor skill used by children and adolescents in leisure and sports activities. It is defined as a form of jumping in which the same foot is used for both propelling (i.e., projecting the body into space) and landing. This motor skill imposes higher demands on children's motor competence and thus distinguishes well-coordinated from less-coordinated ones[53,54]. Hopping is often divided into three main phases: preparation, action/flight, and recovery/landing[54]. To date, most research on hopping in healthy children and adolescents has focused on qualitatively assessing developmental stages[55–57], whereas quantitative measurements, such as spatiotemporal kinematics, have not addressed issues of mental representation[56,58,59].

In the current study, we investigate the effect of the cognitive property of leg preference (i.e., preferred versus non-preferred leg) of hopping on mental representation among healthy female adolescents. We hypothesized that (1) mental representation of SLH of the preferred leg (either right or left) is more structured than that of the non-preferred leg (either right or left), (2) mental representation of SLH of the right preferred leg is more structured than that of the left-preferred leg, (3) mental representation of SLH of the left non-preferred leg is more structured than that of the right non-preferred leg, and (4) a positive correlation between MI vividness and mental representation structure of SLH will be evident.

In study 1, we developed and established BACs for SLH using a codified process. In study 2, we used the developed BACs to investigate the role of leg preference in the mental representation of SLH among healthy female adolescents.

Ethical approval for both studies was granted by Ariel University Research Ethics Committee (AU-HEA-AA-20230614-1). All experiments were performed in accordance with the "Declaration of Helsinki" and relevant guidelines and regulations. All participants in both studies provided written informed consent. For participants under 18 years old, written informed consent was also obtained from parents.

## Study 1

### Methods

#### Participants

A convenience sample was recruited through advertisements in local community and social media groups. Nineteen healthy children aged 8–15 years and four healthy young adults aged 18–24 years) participated in the study: 10 children participated in the motion capture kinematic-functional analysis, and 9 children (age range: 8–15 years; $M = 10.43$, $SD = 1.34$) and 4 young adults (age range: 18–24 years; $M = 20.23$, $SD = 1.49$) participated in the SDA-M procedure.

The inclusion criterion included the ability to physically perform 5 consecutive horizontal hops. The exclusion criteria included developmental impairments diagnosed by a board-certified child pediatrician or neurologist and current musculoskeletal injuries or impairments related to the lower extremities. Participants' leg preference was determined by the leg with which they spontaneously chose to perform a single-leg horizontal hop[60–63].

#### Single-leg hopping task

For motion capture purposes, participants were instructed to hop horizontally on their preferred leg five consecutive times at a comfortable pace. No further instructions were given to participants regarding hopping distance, height or pace. Participants performed the hopping task in a quiet room with adequate space and a rigid floor. Hopping performance was recorded using a video camera that was positioned perpendicularly (see Fig. 1).



**Fig. 1** Motion capture of a 13-year-old participant performing the single-leg hopping task.

### Measuring mental representation

The SDA-M method uses a series of illustrations/figures within the task's functional sequence from the starting position to the ending position. Each figure represents a specific event within the task, termed the basic action concept (BAC)[26,28] (see Fig. 1), that corresponds to functionally meaningful body postures and movement elements[26]. In doing so, each BAC chunks the bodily functional, somatosensory, spatiotemporal, and biomechanical characteristics of the corresponding event within the task[28]. Therefore, these representational units (i.e., BACs) serve as the mental equivalent of functional elementary components of complex movements[44], thus acting as building blocks of mental representation[26,44]. Mental representations are thought to comprise these representational units and their structural composition in relation to one another[28,44]. The SDA-M measurement method objectifies the mental representation and its internal structure in long-term memory by using in the first step a mathematical sorting procedure of successive splitting[26,29], in which each BAC is displayed once as an anchor with each one of the remaining BACs. The participants are asked to classify each pair of BACs as either "related" or "unrelated" to each other. Further details about the procedure can be found in[26,28].

The next (second) step of SDA-M is based on a cluster analysis that uses the proximity measures of step one (splitting procedure). It yields individual divisions of the BACs in tree-like structures, known as dendrograms, which consist of cluster solutions that are determined by a critical Euclidean distance ($d_{crit}$). Junctures below and above the $d_{crit}$ are considered related and unrelated, respectively (see Fig. 3). The resulting cluster solution represents the functional phases of the movement[28,64]. Inter-individual or inter-group differences in representation structures can then be calculated (in the next step) by using structural invariance—λ, which is determined by the number of constructed clusters of the pair-wise cluster solutions, the number of concepts within the constructed clusters, and the average quantities of the constructed clusters.

The λ measure ranges from 0 (*no similarity at all*) to 1 (*dendrograms are identical*). Two cluster solutions (or representation structures) are invariant (i.e., similar) if $\lambda > \lambda_{crit}$ is 0.68 (corresponding to a significance level of $\alpha = 0.05$)[26]. Further details of this procedure can be found in previous studies[26,64].

Additionally, the similarity between a certain structure and a pre-determined reference (ideal') structure for a specific task was calculated using an Adjusted Rand Index (ARI). This measure provides numerical information on which cluster solutions are more organized compared to the reference structure. The values of '1' and '−1' represent the maximal similarity and dissimilarity, respectively[25,65].

## Development of basic action concepts (BACs) of single-leg hopping

We developed the BACs for SLH based on a codified procedure that analyzed the SLH movement cycle, including its biomechanical properties (i.e., kinetic, kinematic, and postural). The procedure included three steps:

*Step 1*: A literature review into SLH was carried out, including developmental[53,66], biomechanical (e.g., kinematic and kinetic)[56,58,59,67,68], qualitative[57,66], and quantitative[56,58,59] components of SLH performance and assessment methods. The following search terms were used: "hopping", "biomechanics", and "kinematics". The following search engines were used: PubMed, MEDLINE, and Google Scholar.

*Step 2*: A focus group consisting of 47 experts, of whom 43 were physical therapists, two were physical activity teachers, one was an exercise trainer, and one was a health researcher. All experts were independent and had no conflicts of interest with the authors or the study. Experts' mean years of experience working with children and adolescents with motor and cognitive disabilities as well as typical development was $M = 7.23 \pm 2.35$ years. The experts were also asked about current gaps in knowledge and understanding in consideration of the available clinical and scientific literature. Next, the experts were asked to complete a computerized survey consisting of three open questions and two multiple-choice questions. The questions concerned functional and biomechanical-kinematic aspects of SLH (e.g., upper and lower extremity positioning during the flight and landing phases; hip, knee and ankle angles during the take-off, flight, landing and stabilizing phases; and trunk positions during these various stages).

*Step 3*: Clinical observations. Ten children (age range: 8–16 years) were videotaped while performing SLH. A video camera (GoPro Hero11; GoPro Inc., CA, USA) was positioned 5 m perpendicular to the participant. Slow video mode was used to allow accurate kinematic analysis. Two physical therapists (ARB, AA) and a movement and mental imagery educator (EF) qualitatively and quantitatively (2-D) visually inspected and analyzed the video clips. Expert focus group, available literature and clinical researcher insights were all integrated to determine the SLH phases and matching BACs. Next, a movement illustrator (EF) created original drawings for each of the identified BACs, and these drawings underwent a finetuning process to best represent the biomechanical and postural properties previously identified. Final versions of the drawings were then created for both the right and left legs. A gender-neutral appearance was chosen to minimize any possible bias towards same or opposite gender information[69,70].

The above-described process (i.e., focus group consensus, available literature and current pilot data) and resulting information were used to determine the 'ideal' (i.e., reference) mental representation structure for SLH, consisting of six BACs and a matching $d_{crit} = 3.55$.

## Procedure and data collection and analysis

The formatted BACs (for the preferred leg only) were tested on 13 participants: nine children and four young adults (see 'Participants' section). Prior to commencing the test, the participants received a detailed verbal explanation of the test's goal and procedure and were encouraged to ask questions. Participants completed two (i.e., for preferred and non-preferred leg) SDA-M tests, presented in a random order (using randomization software).

First, participants were asked to physically perform the motor task (i.e., five consecutive repetitions of SLH) with their chosen preferred leg (see hopping task). Next, the participants completed the SDA-M computerized test using the designated software[28]. The participants sat in front of a 15.6-in. laptop screen in a quiet room. They were verbally instructed to decide whether the presented BACs are related to one another while imaging the movement execution of SLH. Specifically, they were asked as follows: "For each pair of pictures presented on the screen, please decide whether they are functionally related and successive or not". Afterward, the participants completed the splitting task.

## Results

### Development of BACs

The process of developing the BACs yielded a total of 6 BACs within three functional phases (concepts), namely, preparatory, flight, and landing, with each phase consisting of two BACs for the left and right legs (see Figs. 2a, b). A correct solution for the SLH mental structure is presented as a reference structure (see Fig. 3).

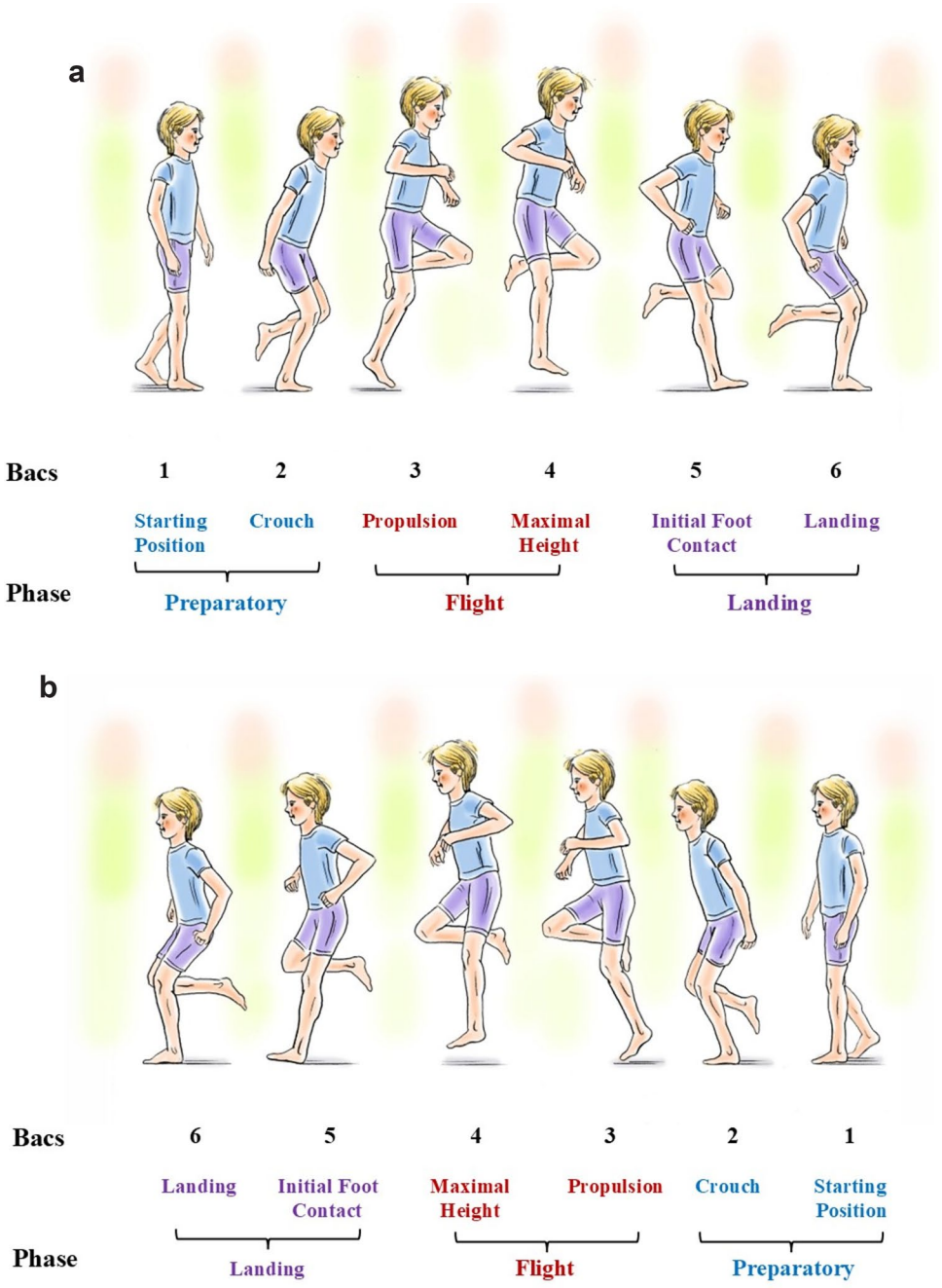


**Fig. 2** (**a**) Basic action concepts of right single-leg hopping. (**b**) Basic action concepts of left single-leg hopping. (*Drawn by*: Eric Franklin)

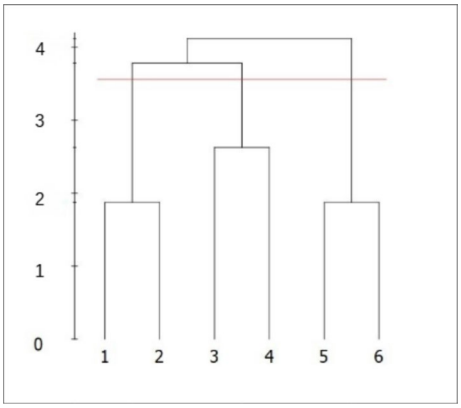


**Fig. 3** Dendrogram of the reference (representative) structure of SLH. *Note* X-axis denotes BACs (1 = starting position, 2 = crouch, 3 = propulsion,4 = maximal height, 5 = initial foot contact, 6 = terminal landing); Y-axis denotes Euclidean distance; horizontal red line denotes $d_{critic}$ of 3.55 ($p = 0.05$).

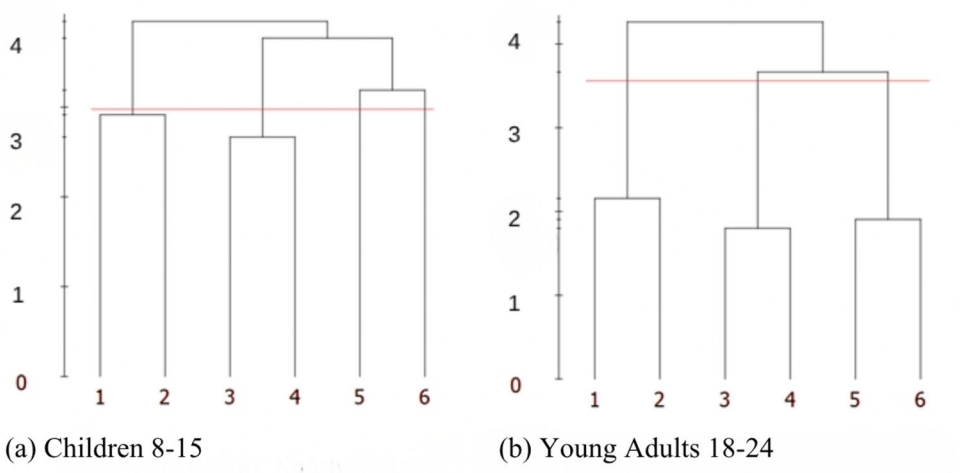


**Fig. 4** Dendrograms of child (**a**) and young adult (**b**) cohorts. *Note* X-axis denotes BACs (1 = starting position, 2 = crouch, 3 = propulsion, 4 = maximal height, 5 = initial foot contact, 6 = terminal landing); Y-axis denotes Euclidean distance; horizontal red line denotes $d_{critic}$; $p < 0.05$ and $d_{crit} = 3.55$ for both cohorts.

### Age-related differences in mental representation

Significant differences were detected between children and young adults ($\lambda = 0.52$, $\lambda_{crit} = 0.68$; $p < 0.05$). The dendrogram for the children's cohort displayed a less structured overall hopping mental representation, whereas the dendrogram for the young adult cohort displayed a structured overall hopping mental representation (see Fig. 4). Visual inspection of the dendrograms revealed that in the children's cohort, the preparatory and flight phases but not the landing phase were correctly identified (see Fig. 4a).

Furthermore, comparison of the dendrograms to the 'ideal' reference structure revealed maximal similarity for the young adults (ARI = 1) and lower similarity for the children (ARI = 0.44).

## Discussion of study 1

### Development of the BACs of SLH

In the current study, we applied a novel coding procedure for constructing BACs with functional motor skill. The current procedure relied on a combination of expert focus group, available literature and clinical observations. In doing so, this procedure goes beyond previously reported processes of establishing BACs, which included surveys[49] or completion of the SDA-M test by expert participants[22,50,71] Several studies have reported on the establishment of BACs but with no details regarding the process[22,50,72,73]. One study reported establishing BACs

using expert surveys and a pilot[49]. Herein, we applied a development procedure within which we integrated scientific literature with clinical observations and expert opinions, thus addressing both scientific and clinical aspects.

### The effect of age on mental representation of SLH

The results of study 1 revealed that mental representation of SLH was more structured for younger adults than for children. This age-related difference confirms the sensitivity of the developed BACs and aligns with previous studies suggesting the development of hopping through age[55,66]. The current results support the notion that such development is attributed to, among other things, the development of mental representation[24,53]. Age-related differences in mental representation have been previously reported[46,55,71]. One study used the SDA-M to compare the mental representation of an overhead arm throw between novice and expert athletes in three age band cohorts[49]. The results showed that the youngest athletes (6–12 years; both novices and experts) exhibited similar unstructured mental representations compared to the representations of all three novice cohorts. Another study compared age-related differences in the representation of sequential finger movement among four cohorts (7-, 9-, and 11-year-old children and adults 19–23 years old) based on chronometry (i.e., comparing time durations for actual versus imaged tasks). The results revealed a more structured mental representation for adults than for all children and a less structured mental representation for the 7-year-old cohort. Interestingly, no difference was detected between the 9- and 11-year cohorts[74]. Conflicting findings regarding age-related MI ability (via a mental rotation task) showed insignificant differences between 10–11 and 12–13 years and adults. However, younger children presented significantly lower performance in accuracy and response time compared to older children and adults ($p < 0.05$)[75].

These results suggest non-linear development of the motor system and mental representation through age. Taken together, these results and those in previous literature suggest that age affects hopping motor proficiency[53]. We formulated two (8–15 and 18–24 years) cohorts that were likely to adequately differ in their hopping-related cognitive and motor capabilities.

### Identified BACs of single-leg hopping

The children's cohort (age range: 8–15 years) correctly identified all phases but landing. This finding may be attributed to the relative complexity of the landing phase in the SLH, which is derived from its requirement for stability and force absorption. Support for this motor complexity can be found in the variability in landing biomechanics even among athletes[76].

## Study 2

### Methods

#### Participants

Thirty-eight healthy female adolescents (*M* age: 16.07 ± 0.33; range: 15.6–16.6 years) participated in this study. All participants were recruited from a designated university program that is offered and planned for youth students. The inclusion criterion was the ability to perform 5 consecutive SLHs (right and left foot). The exclusion criteria included developmental impairments diagnosed by a board-certified pediatrician or neurologist and current injuries or impairments in the lower extremities. The participants' demographics are presented in Table 1. Thirty-one (81.5%) participants exhibited a right-preferred leg and seven (18.42%) exhibited a left-preferred leg (herein referred to as the 'right-preferred' and 'left-preferred' cohorts, respectively). Thirty-five (92.1%)

**Table 1** Participants' demographics (mean ± SD) and t tests between the right and left preferred leg of hopping.

| Variable | All (N = 38) | Right-Preferred leg (N = 31) | Left-preferred leg (N = 7) | t (df = 36) | $p^{!}$ |
|---|---|---|---|---|---|
| Age (Years) | 16.04 ± 0.34 | 16.07 ± 0.33 | 15.9 ± 4.21 | 0.32 | 0.36 |
| Weight (kg) | 59.4 ± 12.41 | 60.88 ± 13 | 52.85 ± 6.54 | 1.57 | 0.02* |
| Height (m) | 1.61 ± 0.66 | 1.61 ± 0.06 | 1.63 ± 0.07 | −0.7 | 0.54 |
| Physical Activity (hrs/week) | 1.89 ± 1.87 | 1.89 ± 0.33 | 1.64 ± 0.62 | 0.328 | 0.73 |
| VMIQ-2_ Total | 91.05 ± 29.63 | 88.64 ± 27.55 | 101.71 ± 38.16 | −1.05 | 0.41 |
| VMIQ-2_ Visual External | 32.16 ± 10.73 | 29.56 ± 12.44 | 30.42 ± 15.56 | −1.8 | 0.15 |
| VMIQ-2_ Visual Internal | 29.16 ± 11.42 | 28.36 ± 11.36 | 32.71 ± 11.87 | −0.9 | 0.40 |
| VMIQ-2_ Kinesthetic | 29.72 ± 12.84 | 29.55 ± 12.88 | 29.15 ± 16.6 | −0.15 | 0.89 |

VMIQ-2 = Vividness of Movement Imagery Questionnaire-2; ! = Independent t test detected differences between groups; * = $p < 0.05$.

participants reported right-hand dominance, and three (7.89%) participants reported left-hand dominance. Thirty-two (84.2%) participants exhibited ipsilateral leg and hand preference.

### Single-leg hopping task

The identical hopping task (including instructions for participants) used in study 1 was used for study 2.

## Outcome measures

*Handedness*. The use of the writing hand was reported by participants.

*Leg Preference*. Participants' leg preference was determined by the leg with which they chose to physically perform the SLH (i.e., actual preference), which is in line with standard motor performance tests[60,61] and previous research[17] Additionally, participants completed a laterality questionnaire consisting of 3 questions ("Which leg do you feel is stronger?"; "Which leg do you feel you better balance on?"; and "Which leg do you use for landing from a jump?")[77].

*Motor Imagery Ability*. Vividness of MI was measured using the Vividness of Movement Imagery Questionnaire Revised Version (VMIQ-2)[78,79]. The 36-item questionnaire measures the vividness of the MI of twelve daily life actions with varying complexity (e.g., running, jumping sideways, and throwing a stone into water). The participants are asked to rate the vividness of the image created when they image themselves performing the movements. Scores range from 1 (*perfectly clear and as vivid as normal vision or feel of movement*) to 5 (*no image at all, you only 'know' that you are thinking of the skill*), with lower scores reflecting greater imagery vividness. A total score is followed by three sub-scores (i.e., external visual, internal visual, and kinesthetic), reflecting the three MI modalities. This questionnaire was used in healthy children (ages 7–12) and young adults (ages 18–25)[79,80] and was found to be valid ($r = 0.31$, $p < 0.05$) for assessing participants' movement imagery vividness[78]. The Hebrew translation exhibited strong reliability (Cronbach's alpha: 0.91, 0.95, and 0.94 for external, internal, and kinesthetic imagery, respectively). No statistically significant temporal stability differences in mean scores were detected for external imagery [$t(85) = 0.24$; $p = 0.81$; ES = 0.03), internal imagery ($t(84) = 0.58$; $p = 0.65$; ES = 0.06] or kinesthetic imagery [$t(85) = -1.2$; $p = 0.23$; ES = 0.13][81].

## Procedure & data collection

Demographic data (age, height, weight) and physical activity habits (hours per week engaging in moderate to vigorous physical activity) were collected. Participants completed the same SDA-M procedure (see Study 1) for the preferred and non-preferred legs in a counter-balanced order.

### Data analysis

An independent t test was applied to compare the demographic data between the 'right' and 'left-preferred' cohorts. The level of agreement was determined by using crosstabs to detect agreement between each participant's self-reported (based on a laterality questionnaire) and actual (based on actual execution) preferred leg. A $2 \times 2$ chi-square test of association was also conducted to estimate associations between these variables. Mental representation data were analyzed using hierarchical cluster analyses of cohort mean dendrograms for determining structured or unstructured mental representations. Similarity (i.e., lack of difference) between cohorts was determined using structural invariance analysis[26] (step 4 of SDA-M). Next, an Adjusted Rand Analysis was used to compare each cohort to the 'ideal' reference structure. Comparisons between cohorts included (1) 'preferred' (either right or left leg) versus 'non-preferred' (either right or left leg) leg, within cohorts (38 pairs with a total of 76 dendrograms), (2) 'right-preferred' versus 'left-preferred' leg, between cohorts (a total of 38 dendrograms), and (3) 'right non-preferred' and 'left non-preferred' leg, between cohorts (a total of 38 dendrograms). The invariance value ($\lambda$) was defined as $\lambda > \lambda_{crit}$ of 0.68, corresponding to a significance level of $\alpha = 0.05$[28,48]. The percentages of structured (i.e., correctly identified) clusters for the three phases and the whole structure were calculated.

## Results

### Participants' demographics

Non-significant differences in demographic data were detected between the 'right-preferred leg' and 'left-preferred leg' cohorts, except for weight, which was significantly ($p < 0.05$) greater in the right-preferred group (see Table 1). This difference was no longer statistically significant after one participant who weighed 105 kg was excluded from the right-preferred cohort. The level of agreement between the actual preferred leg and laterality questions was 76.3% for "Which leg do you feel is stronger?", 65.7% for "Which leg do you feel you better balance on," and 76% for "Which leg do you use for landing from a jump?". Non-significant associations were detected between the actual preferred leg and the answers to questions 1, 2, and 3 [$\chi^2(1,31) = 0.11$, $p > 0.05$, $\chi^2(1,31) = 0.807$, $p > 0.05$, and $\chi^2(1,31) = 1.938$, $p > 0.05$, respectively]. A significant association [$\chi^2(1,31) = 8.15$, df = 1, $p = 0.04$, $\Phi = 0.46$] was detected between questions 1 ("Which leg do you feel is stronger?") and 2 ("Which leg do you feel you better balance on?") of the laterality questionnaire.

### Identification of mental representation phases

All (100%) participants completed the SDA-M test, with the time to complete the test ranging from 10 to 15 min. Two (5.26%) participants (one with a right preferred leg and one with a left preferred leg) exhibited a fully structured (i.e., all 3 phases and the entire routine) mental representation of their preferred leg. Three (7.89%; all with a right preferred leg) participants exhibited a fully structured mental representation of their non-preferred leg. One participant (with a right-preferred leg) exhibited a fully structured mental representation of both the preferred and non-preferred legs. The percentages of participants who correctly identified each phase are presented in Table 2.

### Preferred versus non-preferred leg mental representations

The 'preferred (either right or left) leg' cohort exhibited a structured mental representation, with all three phases being correctly identified (see Fig. 5a). The 'non-preferred (either right or left) leg' participants exhibited an unstructured mental representation, with only the flight phase (i.e., BACs 3&4) being correctly identified (see Fig. 5b). The mental representation structures of the two cohorts were not similar ($\lambda = 0.499$, $\lambda_{crit} = 0.68$, $p < 0.05$).

**Table 2** Correct identification of mental representation structure (%) by leg preference and hopping phase.

| Group | Phase 1 (Preparatory) | Phase 2 (Flight) | Phase 3 (Landing) | Whole structure |
|---|---|---|---|---|
| Preferred Leg (N = 38) | 31.57 | 15.78 | 15.78 | 5.26 |
| Non- Preferred Leg (N = 38) | 29.94 | 15.78 | 15.78 | 7.89 |
| Rt. Preferred Leg (N = 31) | 22.58 | 12.90 | 16.10 | 3.22 |
| Lt. Preferred Leg (N = 7) | 57.14 | 28.57 | 14.28 | 14.20 |

Values represent the percentage of participants who correctly identified the clusters.

A comparison with the 'ideal' structure revealed maximal similarity (ARI = 1) for the preferred leg and partial similarity (ARI = 0.44) for the non-preferred leg.

### Right versus left preferred leg mental representation

Specifically, the 'right preferred leg' participants exhibited a structured mental representation, with all three phases being correctly identified (see Fig. 5c). Conversely, the 'left preferred leg' cohort exhibited an unstructured mental representation, with only the preparatory phase (i.e., BACs 1&2) being correctly identified (see Fig. 5d). A comparison of the two cohorts revealed no similarity ($\lambda = 0.499$, $\lambda_{crit} = 0.68$, $p < 0.05$), suggesting that the cohorts differed in their mental representation. A comparison with the 'ideal' structure showed identical similarity (ARI = 1) for the right-preferred leg and partial similarity (ARI = 0.44) for the left-preferred leg.

### Right versus left non-preferred leg mental representation

Both the 'right non-preferred leg' and the 'left non-preferred leg' cohorts exhibited an unstructured mental representation (see Figs. 5e, f). However, the 'right non-preferred leg' cohort correctly identified the preparatory (i.e., BACs 1 & 2) phase only (see Fig. 5e), whereas the 'left non-preferred leg' cohort correctly identified the flight (i.e., BACs 3 & 4) phase only (see Fig. 5f). A comparison of the two cohorts showed significant lack of similarity ($\lambda = 0.67$, $\lambda_{crit} = 0.68$, $p < 0.05$), suggesting that the two cohorts differed in their unstructured mental representation (although the $\lambda$ value was close to $\lambda_{crit}$). Furthermore, compared with the ideal structure, both cohorts exhibited the same degree of partial similarity (ARI = 0.44).

### Motor imagery vividness

Considering participants' MI vividness, non-significant ($p > 0.05$) differences were observed among the preference cohorts in all three sub-scores (see Table 1). Compared with the 'left-preferred' leg cohort, the 'right-preferred' leg cohort tended (all $ps > 0.05$) toward lower (i.e., better) imagery vividness for total, visual-external and visual-internal sub-scores (see Table 1).

## Discussion of study 2

### Participants' demographic data

The current ratio of 81.5% of participants exhibiting right-leg preference and 18.4% exhibiting left-leg preference reflects the left:right preference distribution in the general population (21.40–25.90%: 78.6–74.1%)[11]. However, the left- to right-preferred leg ratio in the current sample, although reflecting the general population, yielded a small sample (N = 7) of left-preferred participants. This could have biased the results; thus, the results must be interpreted with caution. Interestingly, all participants but one (in the right-preferred' cohort) maintained physical

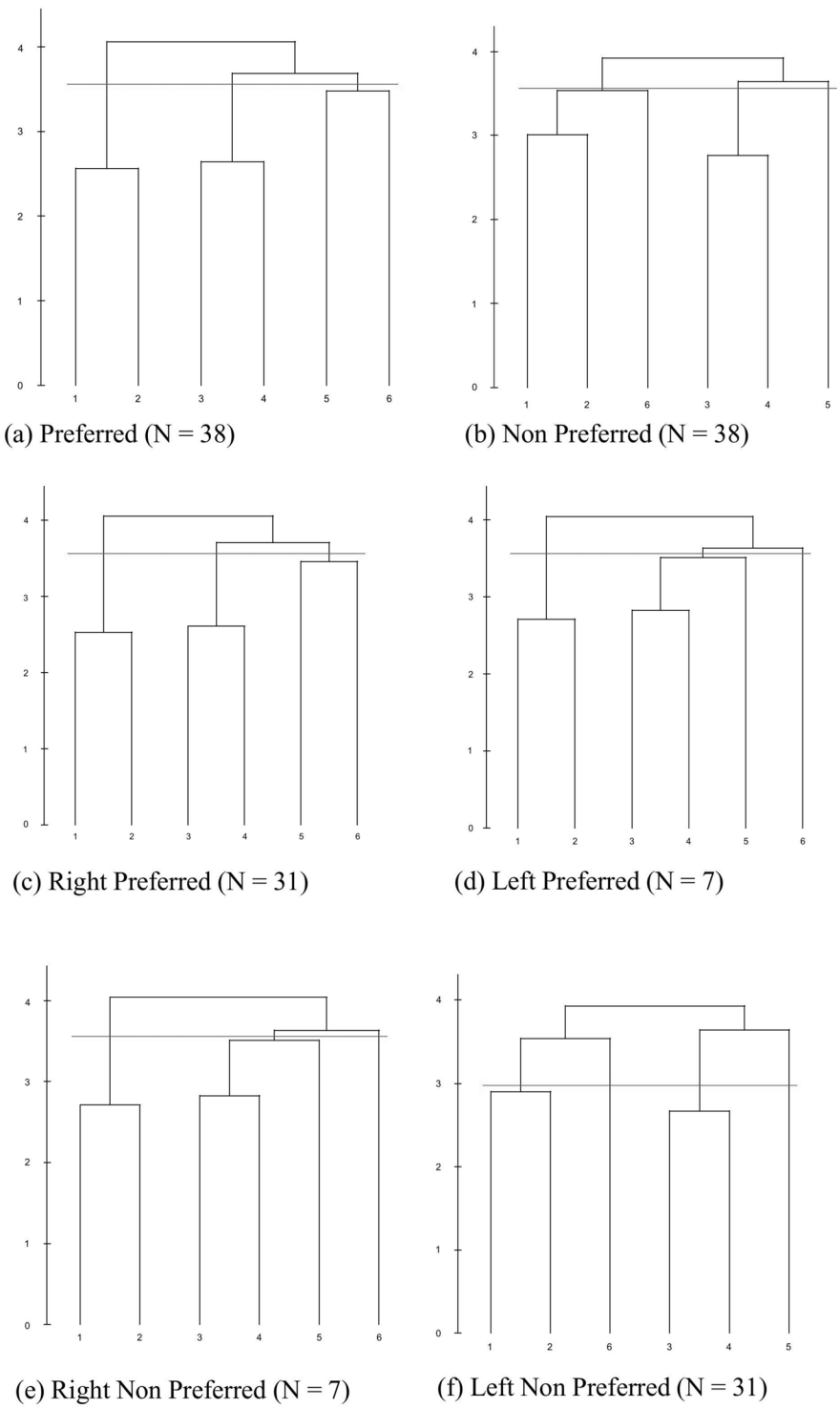


**Fig. 5** Mental representation dendrograms by cohort type. *Note* The X-axis denotes BACs (1 = starting position, 2 = crouch, 3 = propulsion, 4 = maximal height, 5 = initial foot contact, 6 = terminal landing); Y-axis denotes Euclidean distance; horizontal red line denotes $d_{critic}$; $p < 0.05$ and $d_{crit} = 3.55$ for all cohorts.

activity habits below health recommendations (i.e., six hours weekly;[82,83] regardless of leg preference. Two participants only nearly met (i.e., five hours weekly) these recommendations. A low level of physical activity reflects lower exposure to and experience with various motor skills, thus potentially hampering the participants' mental representations[65].

### Participants' leg preference

The non-significant association between self-reported (via questionnaire) and actual chosen (via physical performance) preferred leg raises the question of which method is most reliable for determining leg dominance in clinical and research settings. That said, the current finding of a 65–76% level of agreement between self-reported and actual preferred leg is in line with a previously reported 70% level of agreement found in a variety of lower extremity motor tasks, including SLH, among 20 healthy adult (*M* age: 36 ± 15 years) women[84].

### Correctly identified phases of mental representation

All (100%) participants successfully completed the SDA-M test, with 5.26–7.89% (range within all cohorts; non-significant differences in distribution among cohorts) of participants who correctly identified all three phases of the SLH mental representation. These findings may suggest adequate sensitivity of the developed BACs, although no previous data regarding BACs' norms are available. Specifically, the finding that phase one (preparatory) was better (in percentages) identified than phases two (flight) and three (landing) in all cohorts can be attributed to (1) the preparatory phase's relative ease of performance compared with the flight and landing phases. This relative ease can be derived from the flight and landing phases being more complex components of hopping[76], thus possibly challenging the identification of these phases[74] and (2) the preparatory phase being a crucial building block of hopping, which is thus practiced more extensively, including prior to successfully executing the take-off and/or landing phases.

### Effects of preferred versus non-preferred leg on mental representation

This study is the first to use the SDA-M procedure within the context of side preference. In doing so, our preliminary results shed light on the effect of side dominance on cognitive spheres, namely, mental representation of motor tasks. Compared with the 'non-preferred leg' cohort (which correctly identified the flight phase only), the 'preferred leg' cohort exhibited a significantly more structured mental representation. This finding implies a positive association between the extent of motor use (which is presumably greater for the preferred leg) and the accuracy of mental representation. Support for this association is provided by studies showing that experts, who hold greater experience with a motor task, maintain mental representations that are more structured than novices[22,49,50]. Such an association between actual physical and mental-cognitive components supports mental representation as one mechanism underpinning the mutual interaction evident by action-perception coupling.

### Effects of right versus left preferred leg on mental representation

Compared with the 'left-preferred leg' cohort, the 'right-preferred leg' cohort exhibited a significantly better structured mental representation (who correctly identified the preparatory phase only). This dissimilarity between the cohorts can be attributed to left hemisphere motor superiority[3,85], which includes intrinsic motor network connectivity[4] and motor planning[42,86]. Such lateral superiority promotes motor development on the contralateral side in childhood and adolescence[4] which can be reflected in more structured mental representation, as evident in the current findings of female adolescents.

Our findings align with previous literature showing superior cognitive–motor performance associated with the left hemisphere (i.e., right-side preference). Participants with right-hand dominance demonstrated shorter reaction times and a higher percentage of correct responses on a hand mental rotation task compared with left-handed participants[52]. Similarly, we found that participants with right-hand dominance recognized their dominant hand more accurately than those with left-hand dominance. Additional evidence comes from studies of stroke survivors showing greater motor–cognitive deficits following left- than right-hemisphere damage. Specifically,

left-hemisphere stroke affected movement velocity in both the contralateral and ipsilateral hands, whereas right-hemisphere stroke affected only the contralateral hand[42].

### Effects of the right and left non-preferred leg on mental representation

Both the 'right' and 'left non-preferred leg' cohorts exhibited an unstructured mental representation, with an identical degree of dissimilarity (ARI = 0.44) compared with the pre-determined 'ideal' mental structure. These results do not support our hypothesis regarding a better mental representation structure for the left-preferred leg. Although we failed to find literature on differences in mental representation between the non-preferred extremities, the current findings suggest that left hemisphere motor superiority may be limited to the preferred leg only. Future research is recommended on whether such a selective motor superiority is accompanied by a matching selective motor execution (e.g., biomechanics). Specifically, we propose conducting biomechanical and functional studies that compare left and right-preferred and non-preferred lower extremity motor capabilities.

### Mental representation and motor imagery ability

The mutual association between mental representation and MI[87] suggests a potential role for MI ability in accessing, creating, and using mental representation[30,87], including within the SDA-M framework[28]. As such, our preliminary findings of somewhat better MI ability in the 'right-preferred leg' cohort ($p > 0.05$; see Table 1) can be associated with this cohort's better performance on the SDA-M test (although limited to the preferred leg). Future studies should, however, further investigate the nature of such potential associations.

## General discussion

The present study contributes to the current knowledge regarding action-perception coupling via two streams: First, we describe a codified process for developing basic action concepts (BACs) of mental representation of a motor task. Such a comprehensive approach that merges scientific and clinical spheres addresses issues of objectivity and reliability, which are associated with previously reported methods used for capturing individuals' knowledge about a task, such as interviews, questionnaires and cognitive tasks[88]. Specifically, study 1 confirmed the suitability of the developed BACs for quantifying mental representation of single-leg hopping. The demonstrated effect of age, although it relies on a small sample in which younger adults demonstrated a more structured mental representation than children, supports theories of cognitive-motor development[89,90]. Specifically, the finding of age-related differences in mental representation between children and adults can be attributed to the development and refinement of the parietal cortex[74], including its effect on motor imagery (MI)[91–93] and the association between the two[37].

Second, we used the SDA-M procedure to investigate the role of leg preference on the cognitive spheres underpinning motor planning, execution and control in a sample of healthy female adolescents. Specifically, the findings of study 2 provide evidence for the relative advantage of right-leg preference for mental representation. Although the SDA-M has been widely applied to examine differences between experts and novices and across developmental stages, its use to investigate the influence of limb preference on mental representation constitutes a novel extension of this method. These findings may suggest that side preference, specifically right-side preference, contributes to the structure and accuracy of mental representations, which may have a bidirectional connection with motor planning and control. Taken together, these findings may support action- perception coupling by reinforcing the essential role of the left hemisphere in motor planning, execution and control of both real and imaged movements[42,52].

Future research is needed to examine the cognitive asymmetry in mental representation found in the present study and whether it reflects asymmetry in motor execution[42,94]. Even so, the heterogeneity of research findings

regarding age-related differences in mental representation suggests a compound interaction between age and mental representation development[48,49,74]. Studies investigating the mediating and moderating roles of various factors, such as a task's motor and cognitive level of complexity (e.g., inter-segmental coordination), on mental representation and its development throughout life are still needed. Acquiring such knowledge can also address the lack of normative data regarding SLH kinematics[58].

To our knowledge, this is the first study to report quantitative data concerning BACs, such as the percentage of participants who correctly identified each of them. Further establishing benchmarks for correct identification of BACs will provide a clearer indication of how well BACs capture different expertise levels and developmental stages and can thus used in both research and clinical settings.

Studying the currently developed BACs at different ages and levels of motor expertise will also allow us to track the development of mental representation and MI abilities from childhood through adulthood[49,95] and focus on how these processes evolve with experience, expertise, and motor and cognitive practice.

The findings of the current study also provide preliminary data regarding MI ability and mental representation in the studied cohort. While MI involves numerous dimensions[96] and subcomponents, the VMIQ-2 questionnaire does not differentiate left-to-right MI abilities. Therefore, future studies should investigate the laterality dimension of MI ability and its mutual association with mental representation.

This study has several limitations, including the small and homogenous sample and the uneven distribution of right versus left preferred legs, although it aligns with the right:left distribution in the general population[11]. Research is needed on additional populations, including those with cognitive-motor impairments. Second, the studied task involved mostly the lower extremities. The effect of side preference on mental representation must also be investigated with respect to upper extremities.

In conclusion, the results of the current study provide data concerning the association between leg preference and mental representation among healthy female adolescents, thus contributing to the current knowledge related to action-perception coupling. As such, it holds potential for advancing scientific and clinical insights related to performance enhancement, injury prevention, and rehabilitation domains.

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**Data availability** Sequence data that support the findings are available upon request from first or corresponding authors.

## Declarations

**Competing interests** The authors declare no competing interests.

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